Wave-Driven Marine Boundary Layers: Implications for Atmospheric Electromagnetics and Ocean Acoustics

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LONG-TERM GOALS

The long-term goal of this effort is to advance our quantitative understanding of the factors affecting signal propagation in the marine environment, essential for radio tracking, communication and guidance applications. A significant issue in this scientific area is the reproducible tendency of models for propagation to overestimate the signal's intensity at the receiver (Barrios and Patterson (2002)). Currently employed algorithms rely on the return signal's intensity for determining the distance to an object, thus a signal misinterpretation has a potentially far-going practical consequences. The situation suggests that physical mechanisms or experimental circumstances responsible for signal degradation, contraction of the coherence radius, etc., are not fully understood and accounted for.

A very important phenomenon influencing radio signals is the formation of evaporation ducts (refractive waveguides) in the first tens of meters over the sea surface. Models for propagation over the ocean that are currently in use, rely on an averaged mesoscale description of the marine atmospheric boundary layer. The only possible answer to the intensity discrepancy that could be sought within this approach is the possiblity of a "leaking" evaporation duct, the possibility that the wavegude lets radiation escape into space. Two other factors, namely the fluctuating refractivity in the boundary layer and the scattering by the ocean surface are generally ignored. An analysis conducted within this effort detemined that an error in a widely adopted model for scattering (Miller et al., (1984)) is, enetirely or parially, responsible for the discrepancy between model predictions and observational results. Also, the complex motion of the atmosphere can be responsible for broadening of the propagating beam, thus reducing its intensity. A recently collected data have produced clear evidence that the boundary layer motion consists of both turbulence and wave effects. Although the role of the turbulence has been studied extensively, the role of the wave effects is largely unknown.

In this context, a goal of this work is to explore the influence on signals of factors and processes in the marine boundary layer that have so far been ignored (e.g. micrometeorological fields). A special attention is given to the multifaceted role of surface waves, one distinct element of the marine environment.

OBJECTIVES

The specific objective of this effort is to quantify the effect of the surface waves, manifested through a modulation of the atmospheric motion and through defining the statistics of the sea surface, on the propagation pattern of a signal in the marine atmospheric boundary layer. We seek a repersenataion of our findings in a form suitable to incorporate into numerical models for signal transmission. Invoking the profound physical similarities between the electromagnetic waves over the ocean and the sound signals in the water, we also consider extending the application of our results to the acoustic case. The

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14. ABSTRACT

The long-term goal of this effort is to advance our quantitative understanding of the factors affecting signal propagation in the marine environment, essential for radio tracking, communication and guidance applications. A significant issue in this scientific area is the reproducible tendency of models for propagation to overestimate the signal’s intensity at the receiver (Barrios and Patterson (2002)). Currently employed algorithms rely on the return signal’s intensity for determining the distance to an object, thus a signal misinterpretation has a potentially far-going practical consequences. The situation suggests that physical mechanisms or experimental circumstances responsible for signal degradation, contraction of the coherence radius, etc., are not fully understood and accounted for.

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ultimate objective is to eliminate particular contributor to the discrepancy between measurements and modeling results and thus make numerical models for propagation more accurate.

Figure 1. The Air-sea interaction tower with the instruments array during the CBLAST experiment. Measurements of wind velocity, atmospheric temperature and humidity, pressure fluctuations, and surface elevation were conducted, among others. Photograph courtesy of Dr. Jim Edson.

APPROACH

The data collected during the CBLAST field experiment (Figure 1) exhibit extensive intervals (about 20 % of the experiment's duration) of low winds. This atmospheric flow regime in these conditions is illustrated in Figure 2. At these low wind speeds the shear-driven turbulence has low intensity as well as the turbulent mixing. Such circumstances allow vertical gradients of atmospheric humidity (and refractivity) to be formed and maintained.

Figure 2 demonstrates that in low wind conditions the motion of the whole atmospheric boundary layer is dominated by the wave driving. The essence of mechanism to explain such wave modulation is the fact that the surface motion displaces column of air above it and the mean flow streamlines. If the air column has a stratified distribution of the humidity (refractivity), i.e. in the case of vertical humidity gradient, an instrument at a fixed height will register humidity (refractivity) fluctuations resulting from the displacement. We will assume that the surface waves have a small slope, so the wave-induced fields are linear responses to the surface motion (Hristov *et al.* (2003)). This physical picture will be tha basis of our approach to describing the structure of the boundary layer motion and the influence of the wave modulation on the signal propagation pattern.

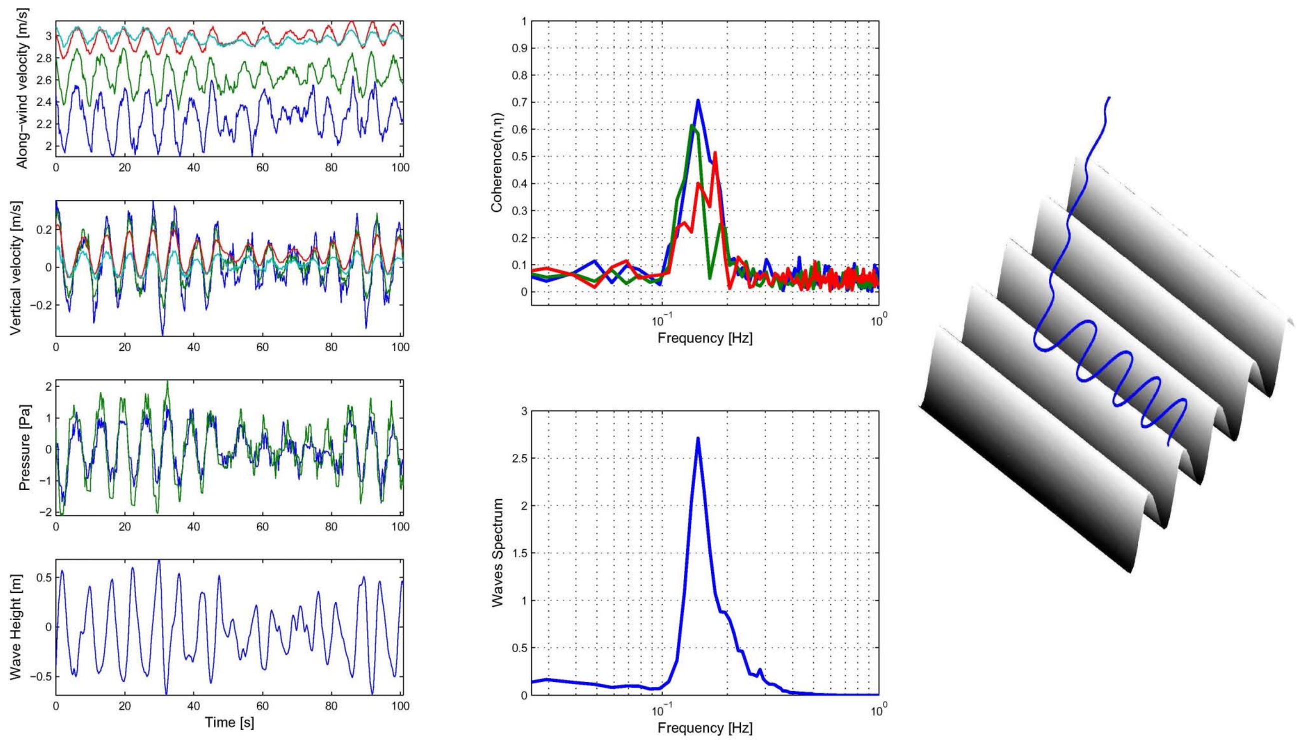

Figure 2. At low wind speeds the wave driving of the atmospheric boundary layer is emphasized. In the left-hand column, the plots show 100s of the measured (not processed) signals of the along-wind velocity at 4 levels from the surface (top plot, colors indicating the height of the instrument from the surface in the order blue -lowest, green, red, cyan - highest), vertical wind velocity (second plot, same color-height correspondence), atmospheric pressure fluctuations (third plot, green-lower, blue-higher instrument), and surface elevation (bottom plot). The plots in the middle column show the coherence between the atmospheric refractivity and the waves (top plot, blue-lowest, green, red-highest instrument), and the surface wave spectrum (bottom plot). On the right-hand side, propagation regimes through idealized periodic refractive media.

WORK COMPLETED

The propagation in an idealized periodic refeactive media can be illustrated by solving the ray-tracing equation. The solutions (Figure 2) show that the beam can be confined along the crests of the refractivity or accumulate displacement when propagating in an oblique direction, thus forming mirages. However, considering that the surface waves are not monochroomatic, solving realistic problems of propagation requires a statistical description of the wave-induced structure of the boundary layer. Important characteristics of the recieved signals, such as statistics of the phase fluctuations, of the intensity or of the angle of arrival depend on characteristics of the media, such as the characteristic function of the velocity field, characteristic function of the two-point correlations of the velocity field, structure function of the atmospheric refractivity (Ishimaru (1978); Tatarskii (1971)). We evaluated these functions, as follows.

We assume that the velocity field in the atmospheric boundary layer $\vec{u}$ can be decomposed into mean $\bar{\vec{u}}$, turbulent $\vec{u}'$ and wave induced $\tilde{\vec{u}}$ components as $\vec{u} = \bar{\vec{u}} + \vec{u}' + \tilde{\vec{u}}$. Within the asumption of small-slope waves (ka<<1) the wave-induced field $\tilde{\vec{u}} \equiv \{\tilde{u}, \tilde{v}\}$ ($\tilde{u}$ being the along-wind component of the wave-induced velocity and $\tilde{v}$ being the vertical component) can be considered as a linear response of the surface wave forcing $\eta = ae^{-ik(x-ct)}$, i.e. $\{\tilde{u}, \tilde{v}\} = \{\phi_{\tilde{u}}, \phi_{\tilde{v}}\}\eta = (u_* / \kappa)\{-(d\varphi / dy), ik\varphi\}\eta$, where φ is a solution of the Rayleigh equation (Hristov *et al.* (2003)).

Characteristic function of the atmospheric velocity. The characteristic function of the atmospheric velocity $\chi(\vec{k}\tau) \equiv \langle \exp(i\vec{k} \cdot \vec{v}\,\tau) \rangle$, through the radar equation (Ishimaru (1978)) determines the correlation function of the signal's electrical field as well as the correlation function of the signal's phase (Wheelon (2001)). Our purpose here is to incorporate the wave effects. Invoking the decomposition $\vec{u} = \bar{\vec{u}} + \vec{u}' + \tilde{\vec{u}}$ and considering the turbulence $\vec{u}'$ and the wave effects $\tilde{\vec{u}} \equiv \{\tilde{u}, \tilde{v}\}$ to be statistically independent, we have shown that the characteristic function factorizes into a turbulent $\chi_{\vec{u}'}(\vec{k}\tau)$ and wave-induced $\chi_{\tilde{\vec{u}}}(\vec{k}\tau)$ multipliers:

$$\chi_{\vec{u}}(\vec{k}\tau) = \chi_{\vec{u}'}(\vec{k}\tau)\chi_{\tilde{\vec{u}}}(\vec{k}\tau)\,.$$

To model the wave-induced part,we employ two considerations. First, that the ocean surface can be viewed as an ergodic random process which is a superposition of independent Fourier modes with random phases. Relying on the central limit theorem, we can reasonably conjecture that the ocean surface has a Gaussian distribution, both in space and time. Second, recalling our assumption that the wave-induced fields $\{\tilde{u}, \tilde{v}\} = \{\phi_{\tilde{u}}, \phi_{\tilde{v}}\}\eta = (u_* / \kappa)\{-(d\varphi / dy), ik\varphi\}\eta$ are linear responses to the wave forcing, and invoking the theorem that a linear transform preserves that Gaussianity of a random process (Parzen (1962)), we can conclude that the wave-induced velocities $\tilde{\vec{u}} \equiv \{\tilde{u}, \tilde{v}\}$ also should be Gaussian random variables. Consequently,

$$p(\tilde{\vec{u}}) = (2\pi\sigma_{\tilde{\vec{u}}}^2)^{-3/2} \exp\left[-\left|\tilde{\vec{u}}\right|^2 / \left(2\sigma_{\tilde{\vec{u}}}^2\right)\right]$$

and the characteristic function for the wave-induced velocity is then

$$\chi_{\tilde{\vec{u}}}(\vec{k}\tau) = \exp\left[-\left(k^2\sigma_{\tilde{\vec{u}}}^2\tau^2\right)/2\right].$$

The standard deviation is obtained considering $\sigma_{\tilde{\vec{u}}}^2 = \sigma_{\tilde{u}}^2 + \sigma_{\tilde{v}}^2$ and that

$$\begin{Bmatrix} \sigma_{\tilde{u}}^2 \\ \sigma_{\tilde{v}}^2 \end{Bmatrix} = \int \begin{Bmatrix} \tilde{u}\tilde{u}^* \\ \tilde{v}\tilde{v}^* \end{Bmatrix} dc = \left(u_* / \kappa\right)^2 \int \begin{Bmatrix} \varphi'(\varphi')^* \\ k^2\phi\phi^* \end{Bmatrix} S_{\eta\eta}\, dc$$

where u_* is the friction velocity and $S_{\eta\eta} = \langle \eta\eta^* \rangle$ is the surface wave spectrum.

The characteristic function of the two-point difference of the atmospheric velocity

$$\chi_{\Delta\vec{u}(\vec{r}_1,\vec{r}_2)}(\vec{k}\tau) = \left\langle \exp\left[i\vec{k}\tau\left(\vec{u}(\vec{r}_1,t) - \vec{u}(\vec{r}_2,t)\right)\right]\right\rangle_{\vec{u}}$$

is needed to calculate the correlation function of the signal's intensity fluctuations (Tatarskii (1971)). For Gaussian processes $\chi_{\Delta\vec{u}(\vec{\rho})}(\vec{k}\tau) = \exp\left[-\frac{1}{2}(\vec{k}\tau)^2\left\langle\left((\vec{k}/k)\cdot\Delta\vec{u}(\vec{\rho},t)\right)^2\right\rangle\right]$, with

$$\left\langle\left((\vec{k}/k)\cdot\Delta\vec{u}(\vec{\rho},t)\right)^2\right\rangle = \frac{1}{k^2}k_ik_jD_{ij}(\vec{\rho}) \text{ and } D_{ij}(\vec{\rho},\vec{r},t) \equiv \left\langle\left[u_i(\vec{r}+\vec{\rho},t) - u_i(\vec{r},t)\right]\left[u_j(\vec{r}+\vec{\rho},t) - u_j(\vec{r},t)\right]\right\rangle.$$

Again, considering the decomposition $\vec{u} = \bar{\vec{u}} + \vec{u}' + \tilde{\vec{u}}$ and that the turbulence $\vec{u}'$ and the wave effects $\tilde{\vec{u}} \equiv \{\tilde{u},\tilde{v}\}$ are uncorrelated and statistically independent, the structure function splits into turbulent $D'_{ij}(\vec{\rho},\vec{r},t)$ and wave-induced $\tilde{D}_{ij}(\vec{\rho},\vec{r},t)$ parts as

$$D_{ij}(\vec{\rho},\vec{r},t) = D'_{ij}(\vec{\rho},\vec{r},t) + \tilde{D}_{ij}(\vec{\rho},\vec{r},t)$$

and the characteristic function factorizes into turbulent and wave-induced multiplyers

$$\chi_{\Delta\vec{u}(\vec{\rho})}(\vec{k}\tau) = \left[\chi_{\Delta\vec{u}'(\vec{\rho})}(\vec{k}\tau)\right]\left[\chi_{\Delta\tilde{\vec{u}}(\vec{\rho})}(\vec{k}\tau)\right].$$

It is important to note that while for isotropic turbulence the turbulent structure function (as well as the corresponding characteristic function) depends only on $\rho = |\vec{r}_1 - \vec{r}_2|$, their wave-induced counterparts are anisotropic. Here again, we can use the solutions of the Rayleigh equation (Hristov *et al.* (2003)) $\{\tilde{u},\tilde{v}\} = \{\phi_{\tilde{u}},\phi_{\tilde{v}}\}\eta = (u_*/\kappa)\{-(d\varphi/dy), ik\varphi\}\eta$ to find the explicit form of $\chi_{\Delta\tilde{\vec{u}}(\vec{\rho})}(\vec{k}\tau)$.

The structure function of the atmospheric refractivity $D_n(\vec{r}_1,\vec{r}_2) = \left\langle\left[n(\vec{r}_1) - n(\vec{r}_2)\right]^2\right\rangle$ occurs when one needs to quantify the statistics of the fluctuations of signal's phase and angle of arrival. Assuming that the fluctuations of atmospheric refractivity over the ocean n consist of turbulent n' and wave-induced $\tilde{n}$ parts $n = n' + \tilde{n}$ and that n' and $\tilde{n}$ are uncorrelated, i.e. $\langle n'\tilde{n}\rangle = 0$, the structure function splits into turbulent $D'_n(\vec{r}_1,\vec{r}_2) == \left\langle\left[n'(\vec{r}_1) - n'(\vec{r}_2)\right]^2\right\rangle$ and wave-induced parts $\tilde{D}_n(\vec{r}_1,\vec{r}_2) = \left\langle\left[\tilde{n}(\vec{r}_1) - \tilde{n}(\vec{r}_2)\right]^2\right\rangle$ as

$$D_n(\vec{r}_1,\vec{r}_2) = D'_n(\vec{r}_1,\vec{r}_2) + \tilde{D}_n(\vec{r}_1,\vec{r}_2).$$

The turbulent structure function $D'_n(\vec{r}_1,\vec{r}_2)$ has been studied extensively since the 1960s (Tatrskii (1971)), yet nothing is known about the wave-induced part $\tilde{D}_n(\vec{r}_1,\vec{r}_2)$. Unlike $D'_n(\vec{r}_1,\vec{r}_2) = D'_n(|\vec{r}_1 - \vec{r}_2|)$, the wave induced term $\tilde{D}_n(\vec{r}_1,\vec{r}_2)$ of the structure function is anisotropic, since the vertical direction plays a distinctly different role than the two horizontal directions.

To evaluate $\tilde{D}_n(\vec{r}_1,\vec{r}_2)$ we will assume that the waves are displacing vertically the mean flow streamlines and the column of air with stratified refractivity. The change in refractivity registered by an instrument at a fixed height is expressed through the vertical gradient of the refractivity $\left(dN(z)/dz\right)$ and the vertical displacement of the streamline at height Z caused by a spectral mode in the wave spectrum with phase speed c, $\delta z = \int \tilde{v}(Z,\vec{k})dt$ as $\tilde{n} = -\left(\frac{dN(Z)}{dZ}\right)(\delta z) = \mathrm{T}(Z,\vec{k})\eta(\vec{k})$. We have introduced $\mathrm{T}(Z,\vec{k})$ as a transfer function, relating the surface displacement $\eta(c)$ and the refractivity fluctuations $\tilde{n}$. From here, introducing $\vec{r} = \vec{R} + Z\vec{e}_z = X\vec{e}_x + Y\vec{e}_y + Z\vec{e}_z$, the correlation function of the refractivity can be expressed as

$$\left\langle \tilde{n}(\vec{R}_1,Z_1)\tilde{n}(\vec{R}_2,Z_2)\right\rangle = \int e^{i\vec{k}\cdot(\vec{R}_1-\vec{R}_2)}\mathrm{T}(Z_1,\vec{k})\mathrm{T}^*(Z_2,\vec{k})S_{\eta\eta}(\vec{k})d\vec{k},$$

which is sufficient to determine also $\left\langle \tilde{n}(\vec{R},Z)\tilde{n}(\vec{R},Z)\right\rangle$ and therefore the wave-induced term of the structure function $\tilde{D}_n(\vec{r}_1,\vec{r}_2)$.

RESULTS

Numerical models for propagation in ducting conditions have shown a persistent tendency to overestimate the intensity at the receiver (Barrios and Patterson (2002)), thus leading to overestimation of the distance to the object producing the radar return as well as to overestimation of the available response time. We reviewed the possible mechanisms for signal degradation, potentially responsible for this deficiency in propagation models. We determined that the widely adopted model for sea surface scattering (Miller *et al.* (1984)) contains an error, which, entirely or partially, leads to the observed error in propagation modeling. We proposed and alternative of the model of Miller *et al.* (1984), which is free of that model deficiencies. We explored the possibility that the atmospheric motion is responsible for broadening of the radar beam, thus effectively reducing its intensity and leading to signal degradation. Data from the CBLAST experiment have indicated that in certain conditions wave modulation can dominate the motion in the atmospheric boundary layer. We quantified the influence of that modulation on the propagation pattern by expressing the characteristic function of the atmospheric velocity, the characteristic function of two-point differences and the structure function of the atmospheric refractivity in a form suitable for incorporating in numerical propagation models.

IMPACT/APPLICATIONS

The analysis outlined above has reviewed and identified several causes for discrepancy between propagation model results and observations. The proposed corrections, in describing the scattering by the rough ocean surface and by quantifying the influence of the atmospheric boundary layer motion on the propagation pattern, are expected to substantially improve the performance of models for signal propagation over the ocean. Although the strong modulation of atmospheric motion has been observed over the mid-latitude Atlantic, it is likely that the phenomenon would be both more prevalent and more pronounced over the Indian Ocean, where low wind conditions are often encountered and where dry air from the surrounding deserts can move over the ocean and cause strong refractive ducts. Because of the profound physical similarities between atmospheric electromagnetics and underwater acoustics, the application of these results can be extended to sound signals in the ocean.

RELATED PROJECTS

The PI is unaware of any related ONR sponsored projects.

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